"QED – Matter, Light and the Void"

Scientific subject and topic:
Physical properties of light

Title / year:
"QED – Matter, Light and the Void" (2005)

Movie producer:
Scienc*e*motion

Director:
Stefan Heusler

Website of movie:
http://www.sciencemotion.de/

Description of movie:
In the first part of the DVD, the properties of light are shown in a puppet animation movie (30 Min.). Prof. Ethereal and his colleague Nick perform experiments about the physical properties of light and try to explain their results by using models. Not all of their explanations are complete, and not all of their ideas lead to correct conclusions. But their discussions and experiments impart methods of scientific research in a humorous way: A scientist should not be satisfied with just one theory and a corresponding experiment but should try to refine his methods of understanding nature, in this case with the final goal to comprehend the fascinating properties of light better and better.

In the second part of the movie, all the models and experiments are explained on a scientific level using mathematical formulas. In this part, facts of modern research are presented, culminating finally in the theory of quantum electrodynamics (QED). The level of the scenes (about 30) varies between high-school and university level, depending on the difficulty of the specific topic related to the question "What is light?"

Link to Trailer Site:
http://www.sciencemotion.de/

Buy DVD:
Order the DVD for EUR 20.00 plus shipping charge on the website
http://www.sciencemotion.de/

Title of scene:
Electromagnetic Fields

Video clip or still:
Chapter 3, Artistic Part

Time interval:
4:20 until the end of the scene

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
electric field, magnetic field, Lorentz force, Coulomb force, special relativity

Description of scene:

Prof. Ethereal and his assistant Nick present a gas discharge experiment.
You need a metal point surrounded by gas such as normal air. Then a high voltage is applied to the metal point. Thus an electrical field is created which is maximal on the metal point. The charges of the gas molecules are attracted by the force (Coulomb force) created through the electrical field. Some of them disintegrate and generate a current which we perceive as a flash. Thus, the highly charged metal point neutralizes through the surrounding gas. A lightning rod works according to the same principle (but it's the other way around, the metal point is neutral and the cloud is charged).

In the next section, Nick visualizes a magnetic field by using iron filings. Magnetic fields neither have a beginning nor an ending. They always run in a circle.

After having introduced electric and magnetic fields experimentally, Prof. Ethereal presents his model for fields: A mountain landscape. In the mountains a snowball is pulled downwards by a force. The direction of this force defines the *gradient* field. The (static) electric field is a gradient field, pointing from the top of the mountain into the valley.
In contrast to the gradient field, the *curl field* winds around the mountain on a contour line. Magnetic fields are always *curl fields*. Magnetic fields only occur if charges *move* with some velocity.

Finally, Prof Ethereal and Nick demonstrate the *Lorentz force* in the last experiment of the chapter: A current is flowing through a metal swing which is located in a magnetic field. Only moving electrons (= an electric current) feel a force in the magnetic field. The scene culminates in a great idea from Nick: Motion is relative. A moving electron turns into a static electron if you fly together with it! This gedanken experiment culminates in the conclusion that electric and magnetic fields are two sides of the same coin as an electric field is transformed into a magnetic field if you change your point of view. The unified theory of both is called *electromagnetism* which was formulated by Maxwell in the 19th century.

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Basic level

Imagine you are sitting in a car on the motorway. While the car is moving you can look through your window and watch the other cars driving on the same motorway. Now, there is a red car in front of you. Basically, three things can happen.

1) Your car is coming closer and closer to this red car. Then your car is moving at a higher speed than the red car.
2) The red car is rushing away from you. Then your car is moving at a lower speed than the red one.
3) The distance between your car and the red car does not change. Obviously, in this case, both cars have exactly the same velocity. If you measure the velocity of the red car from your point of view, it is *zero* because both cars are moving at the same speed.

If a policeman who is standing near the motorway measured the speed of your car and the red car, he would agree that both velocities were the same. However, in comparison to the third case, the velocity of the red car is not zero from his point of view, but for example 100 km/h. Thus, motion is relative. It depends on the point of view of the observer.

In the movie, we show this effect by using rockets which are moving at the same speed in the same direction. From the perspective of one rocket, the velocity of the other rockets is *zero.* For an outside observer, all rockets move at the same speed.

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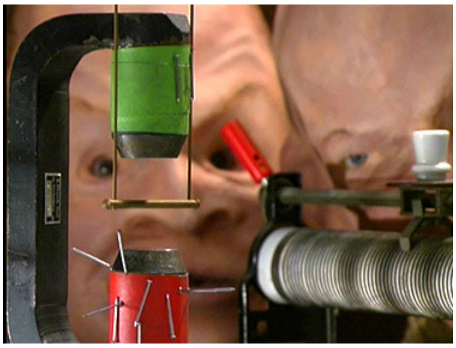
Advanced level

In the 19th century, a lot of experiments revealed more and more properties of electromagnetism. Two important discoveries were:

1) The protons and electrons in the atom are electrically charged. These charges exactly compensate each other. This is quite astonishing: The electron is a point-like, elementary particle. The proton is not. It consists of three quarks. Nevertheless, the charge of the proton is exactly the same as the charge of the electron except for the sign.
2) The interaction between charges is mediated by photons. Photons couple to electrically charged particles such as electrons, positrons and protons. Photons are quantized electromagnetic waves. “Quantized” means that one photon has the energy E = h*v (h is Planck’s constant, v the frequency of the photon). “Electromagnetic wave” means that the photon oscillates with a certain frequency v between electric and magnetic field strength while it is propagating through the space.

Let’s have a closer look at the movie’s experiment with the conductive swing in a constant magnetic field.



Only moving electrons (= a current through the metal swing) feel a force in the magnetic field. Now, if a current of electrons is flowing through the conductive swing, the electrons feel a force in this field, the so-called Lorentz force.

However, from the viewpoint of an observer who is moving at the same speed as one given electron the velocity of this electron is zero. Therefore the Lorentz force also disappears from the observer’s view. Still, this electron feels a force because the laws of physics are independent of the observer’s perspective. The Lorentz force transforms into the Coulomb force (= electric force) through the change of perspective.
For this reason the Coulomb and the Lorentz force are two sides of the same medal. It depends on the observer’s perspective whether the force is perceived as an electric or a magnetic force.

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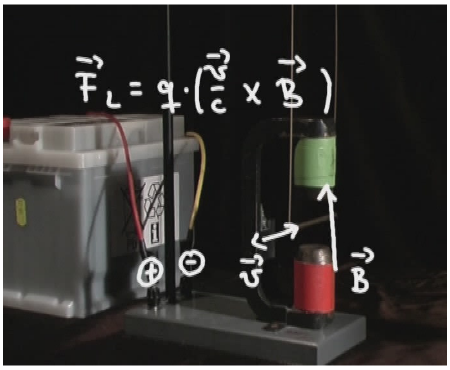
Scientific level

We want to discuss the relation between the following experimental observations:



1. A current of moving electrons a magnetic field.
2. Moving test charges in a magnetic field feel the Lorentz force.
3. Static electrons create an electric field.
4. Static test charges in an electric field feel the Coulomb force.

In the classical theory of electromagnetism, charges which *create* electric and magnetic fields are distinguished from test charges which *feel a force* in this field. Self-interaction of charges with its "own" field is ignored in Maxwell's classical theory.

Let's have a look at a wire in which a current is flowing. The simplest possible case would be if all negatively charged electrons were moving at the same speed w and the atomic trunks had the same fixed distance l from each other. In the laboratory system, the charges of the atomic trunks and the moving electrons neutralize each other. The wire is neutral. Therefore the electric field outside the wire is zero. However, around the wire, a magnetic curl field emerges due to the current of electrons.

Then, let's imagine a test charge q moving outside the wire at the speed v parallel to the direction of the current in the wire. This test charge does not feel the Coulomb force because the wire is electrically neutral. But it feels the Lorentz force in radial direction. This is the scenario from the observer's point of view in the laboratory system.
We change the perspective and are moving together with one electron in the wire. From the perspective of the electron, the positively charged atomic trunks are moving in the opposite direction. Therefore, a magnetic field emerges outside the wire also from the point of the electron's view.

But what happens to the test charge? Suppose, that the velocity v of the test charge q and the velocity of the electrons in the wire are the same, v = w. From the electrons' point of view in the wire, the test charge is at rest. Even if there is a magnetic field, the test charge cannot be affected by it, because the Lorentz force vanishes for static test charges. But from the viewpoint of the test charge there is still a force in radial direction. As this force cannot be the Lorentz force it must be the Coulomb force.

We come to the conclusion that from the perspective of the observer co-moving with the electrons and the test charge, the wire is not neutral but electrically charged. This charge creates an electric field which is accelerating the test charge in radial direction.

It might be a surprise that the reason for this electric field is length contraction which follows from the theory of *special relativity.*
Since the wire is electrically neutral in the laboratory system, the distance between the static atomic trunks $d_{trunks}(0)$ and the moving electrons $d_{elec}(w)$ is the same, $d_{trunks}(0) = d_{elec}(w)$.
On account of the length contraction, the distance $d_{elec}(w)$ of the electrons, moving with velocity w in the laboratory system, is smaller than in the rest system of the electrons:

$$d_{trunks}(0) = d_{elec}(w) = \frac{d_{elec}(0)}{\sqrt{1-\left(\frac{w}{c}\right)^2}}$$

Both from the perspective of the electrons in the wire and the test charge q, the atomic trunks are moving at –w, and we find

$$d_{trunks}(-w) = \frac{d_{trunks}(0)}{\sqrt{1-\left(\frac{w}{c}\right)^2}} = \frac{d_{elec}(0)}{1-\left(\frac{w}{c}\right)^2} \neq d_{elec}(0)$$

Indeed, an electric field emerges, because the positive and negative charge densities do not completely neutralize each other. This electric field has the same effect on the test charge q as the magnetic field in the laboratory system. These two fields are just two sides of the same coin.

Websites about electromagnetism and special relativity
http://en.wikipedia.org/wiki/Electromagnetism
http://en.wikipedia.org/wiki/Relativistic_electromagnetism